WIND EROSION OF MANCOS SHALE BADLAND RIDGES BY SUDDEN DROPS IN PRESSURE

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ABSTRACT

One process of erosion of Mancos Shale badlands near Hanksville, Utah, appears to be caused by nearly instantaneous drops in air pressure accompanying gusts of wind. A series of sharp-crested bedrock ridges trend nearly perpendicular to the strong, gusty southwesterly winds that precede cold fronts passing through the area. The Bernoulli effect, resulting from the explosive onset of wind gusts in which the wind over the ridges can accelerate from 7 to 14 m s^{-1}, can cause nearly instantaneous pressure drops of 1·27 mmHg. This provides a unit lifting force of 0·01697 N. Since the average gravitational force acting on a unit area of the crust is only 0·00883 N, this force is sufficient to lift the crust, exposing the underlying weathered shale chips to further wind erosion.

Soils susceptible to this type of erosion consist of polygonally cracked surface crust averaging 1·2 cm thick overlying a porous subsoil of silt-sized shale chips. The arid environment permits complete soil drying between weather fronts, greatly reducing the cohesion that would occur if the soil were moist.

The pressure drops, and the erosion caused by them, were observed on the lee side of bedrock ridges about 10 m high, within 1 m of the ridge crest. Landforms resulting from this process are micro-cirque forms located near the ridge crests. Continued development of micro-cirques eventually forms cliffs on the lee sides of the ridges.

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INTRODUCTION

In a portion of southeastern Utah (Figure 1) the Mancos Shale outcrops over several hundred square kilometres. This area is located between the Henry Mountains and the Waterpocket Fold, on the axis of the Henry Basin. A representative area of the Blue Gate Shale Member, approximately 20 km west of Hanksville, Utah, on the Town Point 7·5 minute Quadrangle, was used for studies of the processes of fluvial erosion and mass movement. During this study, a process of wind erosion that can be described as 'soil vacuuming' was discovered. This paper describes the process, the forces causing it, and the resulting landforms.

Wind is a well-recognized geomorphic agent in desert regions, but references to erosion by a vacuuming process are absent, possibly because most work has been done in deserts of sand or bedrock. An extensive search of several electronic databases has failed to turn up any references to this process. The extent to which the vacuuming process is commonplace on shale deserts remains to be determined.

The North Caineville study site is located in the NE 1/4, Sec. 21, T. 28 S., R. 9 E. at an elevation of about 1400 m. The nearest weather station used to gather wind data is located in Hanksville. Precipitation there averages 13 cm per year.

SOILS AND PHYSIOGRAPHY

A set of sharp-crested shale ridges extends out from North Caineville Mesa about 3 km in a southeasterly direction. Slopes are generally 40 degrees. These ridges are separated by broad, flat-floored valleys.

Soils developed on the ridges are paralithic. They consist of a surface crust averaging 1·22 cm thick. This crust is formed of shale chips cemented by gypsum. Measured samples of the crust varied from 0·8 to 2·25 cm thick due to the adhesion of shale chips to the bottom. Desiccation has cracked the crust into polygons typically

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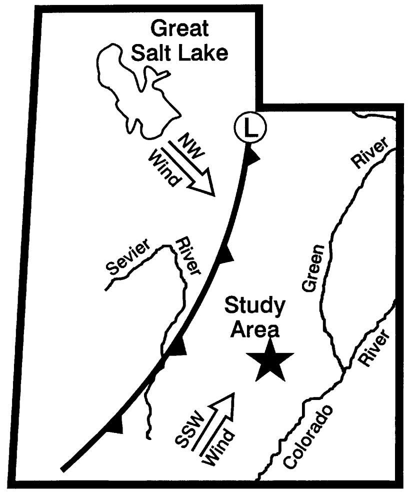

Figure 1. Map of state of Utah showing location of study area. A typical cold front is shown crossing the state from northeast to southwest, with a low pressure area to the north. Wind directions before and behind the front are also shown

5·9 cm across (see Figure 4). One wetting-and-drying cycle is sufficient to form new crust after the old has been removed. The gravitational force acting on the crust averages 0·00883 N but can vary from 0·00618 to 0·01501 N.

Beneath this crustal layer are 5 to 15 cm of shale chips. The upper 2 to 5 cm contains silt- to sand-sized, randomly oriented shale chips. Below this, the chips are horizontal to sub-horizontal. Throughout both zones, the size of the shale chips increases with depth and the soil grades into bedrock with an indefinite boundary.

THE PROCESS

During spring and autumn, cold fronts associated with low pressure centres cross Utah (Figure 1). Annually, ten or more of these fronts produce strong, gusty surface winds in excess of 10 m s^{-1} at the Hanksville weather station. The anemometer at the station is approximately 11 m above ground level. These windy fronts occur primarily during March, April and May; June and October also have above average numbers. Winds preceding these fronts blow from the southwest (200 to 240 degrees) while those following the fronts blow from the northwest (270 to 350 degrees).

The cold front that passed over the Hanksville weather station early on 9 March 1986 was typical. Throughout 8 March winds of 5 to 8 m s^{-1} with gusts of up to 10 m s^{-1}, blowing from the southwest (220 to 240 degrees), were recorded at the Hanksville weather station. There was a short rainfall about midnight. On the morning of 9 March, the winds continued from 220 degrees at 5 m s^{-1} until about 9 am; by 10:30 am they were blowing from the northwest (300 degrees) at 10 m s^{-1} with gusts of up to 15 m s^{-1}. After 11:00 am and for the rest of the day, the winds at Hanksville continued out of the northwest (270 to 350 degrees) at 5 to 8 m s^{-1}.

During the day of 8 March, wind gusts reached 22 m s^{-1} passing over the Mancos Shale ridges near Caineville. The winds were measured 1·5 m above the crest of the ridge, using a hand-held Dwyer Wind Meter. These higher wind velocities over the ridges, compared to those measured at the Hanksville weather station, probably are partially due to the channelling effect of surrounding landforms and partially due to the 1·7-fold amplification of wind velocities over the brows of ridges. Bowen and Lindley (1977) found this 1·7-fold amplification over escarpments with a 45 degree front slope and a 1·8-fold amplification over escarpments with a 27 degree front slope. Ridges in this area typically have slopes of 40 degrees.

On the lee (downwind) side of the ridges, within 0·6 m of the crests, the gusts produced nearly instantaneous, short-lived (less than 1 s) barometric pressure decreases that varied from nearly 0 to 1·27 mmHg and averaged 0·76 mmHg. Measurements on the upwind side showed that the gusts produced no significant changes in air pressure at those locations. These measurements were visually noted from an analogue barometer laid on the

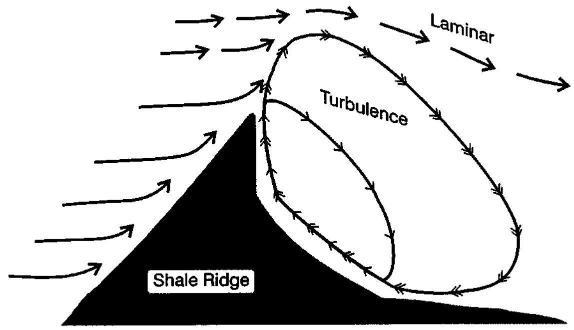

Figure 2. Schematic diagram of a wind gust crossing a Mancos Shale ridge. Single-barbed arrows indicate turbulent zone between wind gusts, while double-barbed arrows show enlarged turbulent zone brought at by sudden increase in wind velocity at initiation of gust. The double-barbed arrows also show the lifting and expansion of turbulent zone on onset of wind gust. In part, the expansion of the turbulent zone leads to lower barometric pressure near top of ridges on lee side

ground surface. Because of the short times of the pressure decreases, a barometer lacking damping mechanisms was used.

The decrease in pressure on the lee side is due to the Bernoulli effect and to the rapid expansion of the turbulent air zone on the lee side of the ridge (Figure 2). Tests with streamers and dust showed that the axis of this turbulent zone rotated parallel to the ridge crest at the sites of the miniature cirque-like features described below. Vertical flutes in the higher cliffs suggest that secondary vertical vortices, like those described by Whitney (1978), may also be present in the lee of the larger features produced by the process.

The soil atmosphere in the voids between chips beneath the crust must remain at ambient pressures during the short interval in which the air above the soil experiences a sudden pressure drop caused by the wind gusts. The maximum observed pressure drop of 1·27 mmHg in the air above the soil provides a unit lifting force of 0·01697 N, nearly twice the average unit force of gravity of 0·00883 N. Table I shows the lifting force produced by different drops in barometric pressure. The resulting forces are sufficient to lift the crustal polygons, exposing them to the wind that efficiently blows them away (Figure 3). This lifting process is termed ‘soil vacuuming’.

Table I. Unit lifting force generated by changes in air pressure

Change in air pressure (mmHg)	Lifting force (N)
0·25	0·00333
0·76	0·01013
1·27	0·01693

Other factors affecting the forces required to lift the crustal polygons are slope angle, friction and cohesion. On a 20 degree slope, typical of the floor of a micro-cirque (described below), the effective gravitational force on a polygon would be reduced by 6 per cent over that on a level surface; while on a 40 degree slope, typical of most side slopes, it would be reduced by 23 per cent.

Counteracting lifting forces are the cohesive and frictional forces working to hold the polygons in place. The importance of these forces varies considerably among polygons. In some instances, polygons are completely separated from adjacent ones; in others, jagged edges interlock to varying degrees. Varying quantities of the underlying shale chips adhere to the crustal polygons, causing the variations in thickness and thus in the resisting force. Although the contributions of these forces are difficult to quantify, the fact that crustal polygons have been observed to be lifted shows that the lifting forces are sufficient to overcome the cohesive and frictional forces.

The vacuuming process and the resulting landforms were observed only on the northeast sides of ridges that are perpendicular to the southwesterly winds. There are several reasons why similar features are not present on the southwest sides of these ridges. First, winds behind the front blow from the northwest, which is along – but not across – the ridges. Consequently, significant pressure drops between soil atmosphere and air do not occur.

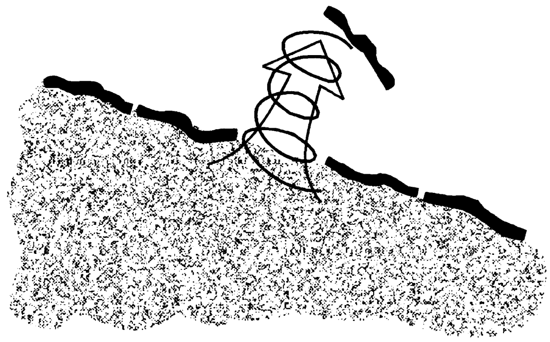

Figure 3. Schematic diagram of polygon of crust being vacuumed off the surface by decreased air pressure above soil while air pressure within the soil remains at ambient levels

Second, precipitation often accompanies cold fronts. Note, for example, the precipitation on the evening of 8 March after soil vacuuming had been observed. This moisture, in the swelling clays that form the soils on the Mancos Shale, would increase both the density and the cohesiveness of the surface layer, making it less likely that the process of vacuuming would operate.

RESULTING FEATURES

Observations of the landforms found in the study area, and of material moved during the passage of a cold front, indicate that soil vacuuming forms distinct erosional features. These features can be ordered on the basis of size (Table II).

The smallest erosional feature is the cavity left by the removal of a single polygon of crust, exposing the underlying shale soil (Figure 4). These single cavities appear to be caused by short-duration, moderate-wind events.

Table II. Erosional features resulting from soil vacuuming

Erosional feature	Relative size
Crustal polygon removed	small, 1 to 10 cm
Patch of crust removed	
Micro-cirques	
Deflation depressions	
Cliffs on lee side of ridges	large, about 10 m

Large, patch-like areas result from a larger and stronger frontal event. In these patches, the crust and some underlying soil has been removed. In many instances, the soil was removed from beneath the crust on the uphill side of the crustal polygons removed by vacuuming, forming cavities (Figure 5). These patches are typically about 3 to 4 m long, measured along the strike of the slope, and up to 2 m wide, measured up and down the slope.

On a slightly larger scale are landforms that resemble micro-cirques. They are apparently formed by repeated wind events (Figure 6). These 1 to 3 m wide and about 1 m deep micro-cirque forms are found on the lee side and immediately below the crests of the shale ridges. The slopes of the side and back walls are typically 60 degrees, while that of the floor is 20 degrees, contrasting with the typical 40 degree slope of these Mancos Shale ridges.

During any one wind event, vacuuming can enlarge the micro-cirque only a few centimetres by removing the thin soil mantle down to bedrock. Weathering between events rapidly prepares surficial material (by slaking and disintegrating the Mancos bedrock) for vacuuming during subsequent events.

Continuation of the process apparently leads to two distinct landforms: cliffs that face in the downwind direction, and closed depressions. Of the two, cliffs are the more common. They vary from about 2 m to over

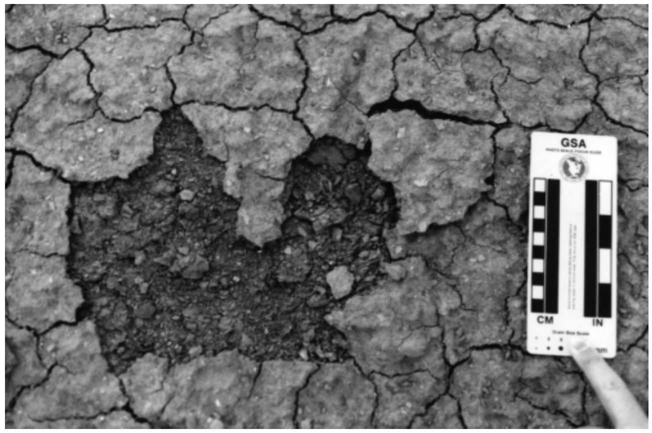

Figure 4. Removal of individual polygons of crust. The underlying, uncemented soil of shale chips is exposed

Figure 5. The crust on the downwind side of this ridge has been removed by soil vacuuming. Note the topographic position, just below the crest of the ridge. Shovel handle is about 0·7 m long

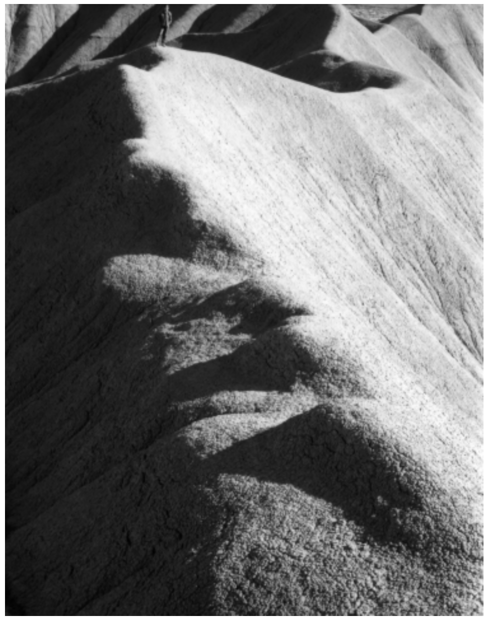

Figure 6. A series of micro-cirques along a ridge crest. The southwest winds preceding the cold fronts blow from right to left. Note the asymmetry of the ridge with no micro-cirques on the right, southwest, side. Note person for scale

10 m high and vary widely in their length. They are covered with a crust only a few millimetres thick. This crust is removed during strong wind events. Cliffs develop from the continued downwasting and enlarging of micro-cirques. Figure 7 shows a ridge with a well-developed lee-side cliff. The upwind slope, of about 40 degrees, is typical of slopes on Mancos Shale ridges. Several lines of evidence indicate that these cliffs are formed by soil vacuuming. Unlike other cliffs in the area, which are formed by stream undercutting, there is no evidence of any type of a water course at their base. Further, these cliffs all face northeastward and have evidence of active soil vacuuming on the slope or a closed depression at their base.

Closed depressions attributable to vacuuming are up to 1 m deep and up to 10 m in diameter (Figure 8). Some are located directly downwind from cliffs, while others are on the crests of broad ridges. Slopes leading to the bottom of the depressions range from 5 to 60 degrees but average about 20 degrees. The floors of the depressions are smooth and covered with desiccation cracks. This surface indicates that sediment is being washed in from the side slopes. There are no soluble rock types, such as limestone or gypsum, within several thousand feet stratigraphically beneath these features. This indicates that the closed depressions are not formed by solution processes.

The process apparently ceases when upwind migration of the micro-cirque or cliff breaks through the ridge. An example is shown in Figure 8. At the point of breakthrough, the sides of the cirque form become cliffs that face both downwind and oblique to the wind. They are thus exposed to erosion by both vacuuming and wind shear.

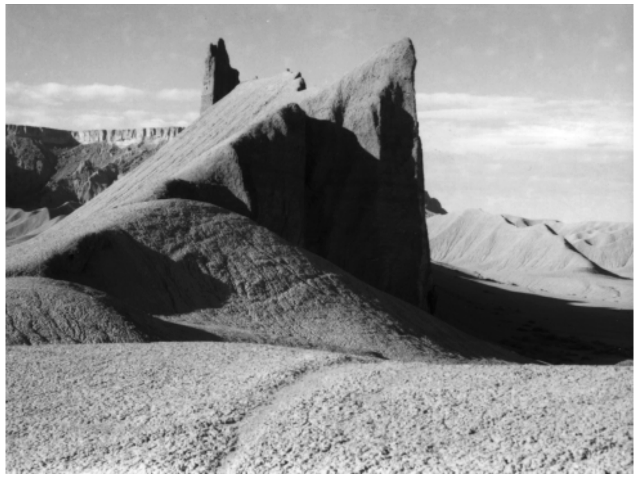

Figure 7. Wind-eroded cliff in Mancos Shale. Southwesterly winds blow from left to right. Person at base of cliff gives scale. Shadow of cliff to right outlines a closed depression

Figure 8. Closed depression downwind of a cliff that has been breached by headward erosion of a micro-cirque. Wind direction is from the right, southwest, to the left, northeast. Note person for scale

Although the distinctive erosional landforms result from the soil vacuuming process, depositional features in the area are similar to those produced by other forms of wind erosion. The polygons found lying near their sources were moved only short distances by vacuuming; further transport carries the silt-sized sediment and concentrates it in rills lower on the slopes or around vegetation. Furthest transport is by dust clouds that remove the sediment from the area.

SPECULATIONS

Although the process of vacuuming has not been reported from other locations, there are similar landforms at other locations, suggesting that vacuuming operates there also. Prerequisites for the vacuuming process are common in arid regions: a crusted soil, a lack of vegetation to reduce near-surface wind velocities, and a shale lithology.

Some roadcuts contain features suggesting that vacuuming has modified their original shape. In these cuts, the cut slope facing the wind has a uniform gradient from top to bottom. However, the side facing downwind has a near vertical slope for the top metre and then an incline down to the borrow ditch.

The edges of alpine plateaus provide another possible environment where vacuuming could operate. Where there is a sharp break between a cliff and the plateau, the trim line of the Krumholtz vegetation (if present) indicates the location of the wind line. There are places below this wind line where all fine-grained material is missing from the soil surface, resulting in a ground surface covered with pebbles and cobbles. The strong gusty winds, common in such localities, may periodically create sudden pressure drops that have vacuumed the fine-grained material off the surface.

CONCLUSIONS

At locations near the crest of Mancos Shale ridges running perpendicular to strong, gusty winds preceding cold fronts, barometric pressure dropped 1·27 mmHg at the onset of wind gusts accelerating the air from 7 to 14 m s^{-1}. Assuming air pressure in the soil remained constant, this instantaneous drop developed a unit lifting force of 0·01679 N. The gravitational force acting on the crust averaged 0·00883 N, and ranged from 0·00618 to 0·01501 N. Thus the lifting force developed by the measured wind gusts exceeded the average resisting force per unit area of the crust by 15 to 90 per cent. This process allows wind erosion by soil vacuuming.

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